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Contributions to the decay of Tb^{160} to Dy^{160}

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With 4 figures in the text

ABSTRACT

The spectra of conversion electrons and photoelectrons have been re-investigated with high resolution and accuracy. Four new transitions have been found. Their intensities are given as well as their multipolarities. Coincidence measurements have been carried out between the different beta branches and the most prominent conversion lines. It was possible to decide between two different decay schemes that have been proposed earlier. The possible existence of an odd parity vibrational band ($K = 0$) is discussed.

Introduction

Tb^{160} ($T_{1/2} = 72\ d$) decays by negatron emission to Dy^{160} which is an even nucleus, expected to possess a spheroidal shape. The decay has been investigated repeatedly with different techniques. Workers using semicircular spectrographs have reported extremely complex conversion spectra comprising some 27 transitions. Perhaps the most comprehensive investigation is that of O. Nathan [1], who has applied most current techniques to the problem. The β-spectrum was found to be separable in the components β_1: 455 keV (22 %), β_2: 575 keV (42 %), β_3: 870 keV (36 %), and β_4: 1765 keV (0.4 %), in agreement with earlier works except with respect to the lowest energy branch. Conversion line measurements with an "orange" spectrometer and gamma intensity measurements with NaJ(Tl) crystals yielded relative conversion coefficients which could be normalized to an absolute scale. Multipolarities could thus be assigned to the transitions. These results are summarized in Table 1. The lines were arranged in a level scheme on the basis of information from (γ,γ) and (β,γ) coincidences.

The (γ,γ) coincidence work by Ofer [2] supports the conclusions arrived at by Nathan [1]. An interesting interpretation was put forward by these authors in terms of the unified model.

Independently, Clark and Knowles [3] investigated the conversion spectrum, using a lens spectrometer, and the gamma spectrum, partly by means of crystal diffraction and partly by photoelectron and scintillation methods. Their results as to the

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[1] On leave from the Egyptian Atomic Energy Commission.

Table 1. Gamma ray energies and intensities.

Clark and Knowles [3]		O. Nathan [1]		Present work	
Energy keV	Abs. int.[a] %	Energy keV ± 1 %	Abs. int. %	Energy keV	Int. %
86.7	14.8	87	10.3	86.8 ± 0.3	
		92		94.3 ± 0.6[b]	0.1[c]
197	4.6	196	8.1	197.0 ± 0.4	
216	3.7	216		215.6 ± 0.4	
298	29.1	298	30	298.6 ± 0.4	
		395	2.6	394.5 ± 1.0	
				681 ± 2[b]	0.55[d]
		744			
		766		764 ± 2[b]	
880	33	876	33	879.3 ± 0.2	
966	38.7	960	35	962.5 ± 0.4	10[e]
		964		966.3 ± 0.3	23[e]
		1076			< 1
				1115.0 ± 1.7	1.9[f]
1179	16.8	1180	16	1177.6 ± 0.3	
				1199.9 ± 0.8	2.9[f]
1274	9.2	1272	7.7	1272.3 ± 0.4	
				1312.4 ± 0.8	2.3[f]

[a] These values have been calculated from the relative intensities by comparison with O. Nathan's value for the 876 keV gamma ray.

[b] Transition seen in internal conversion only.

[c] The M1–E2 admixture is not known. The gamma intensity was calculated by means of an average value of 1.7 for the K conversion coefficient. This should be correct to within ± 30 % for any mixing ratio.

[d] Intensity calculated on the assumption of E2 multipolarity.

[e] Relative intensities normalized to Nathan's value for the 876 keV gamma ray.

[f] Relative intensities normalized to Nathan's value for the 1180 keV gamma ray.

transitions are also compiled in Table I for comparison. The pulse spectrum from a NaI(Tl) crystal was investigated in coincidence with the *L*-conversion line of γ 87 keV. The resulting level scheme has been drawn alongside with that of Nathan [1] (Fig. 1) for easy comparison. There is evidently disagreement on several points.

The present work involves a re-investigation of the internal conversion spectrum and the photo-electron spectrum, using higher resolution and accuracy than could be attained in previous spectrometric study of this isotope. Furthermore, coincidences between the conversion lines and the various beta distributions were carried out.

Internal conversion

The source was produced by irradiating a few mg of very pure Tb_2O_3 for 6 months in the Harwell reactor. A uniform sample was prepared by electroplating onto a 4×20 mm² strip of 0.9 mg/cm² mylar covered with a thin, evaporated layer of silver. The details of this technique are described by Mihelich *et al.* [4]. The single spectra were recorded with a double focusing, flat spectrometer ($\varrho = 50$ cm, $\beta = 3/8$,

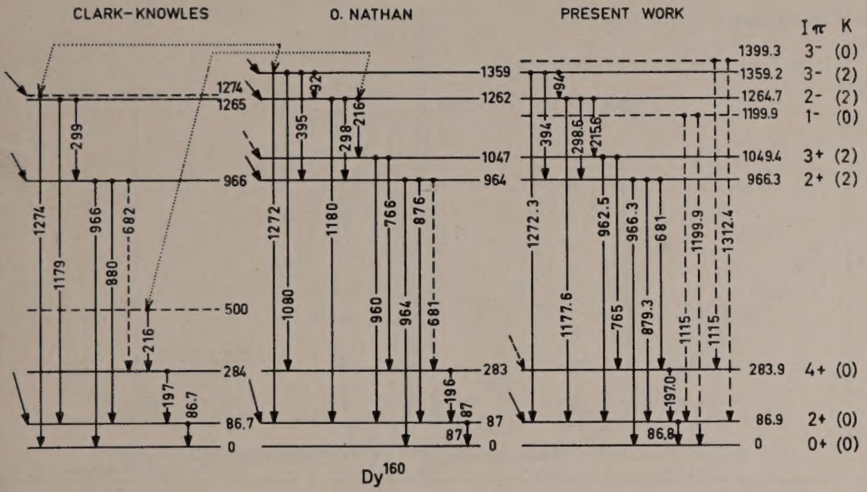

Fig. 1. The different decay schemes drawn for comparison. Most of the spin and parity assignments are those due to Nathan.

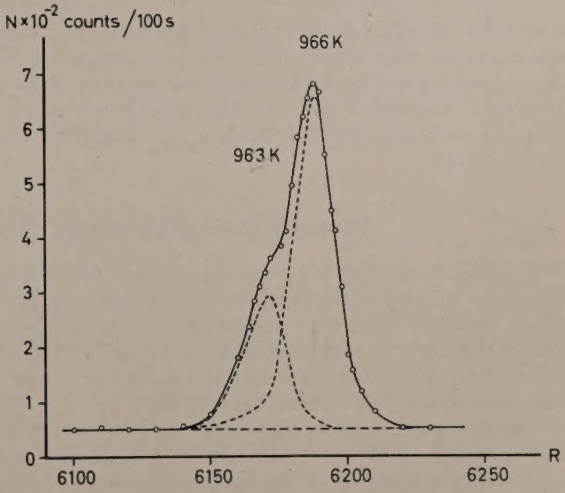

Fig. 2. The 962.5–966.3 keV doublet observed in internal conversion.

iron yoke) yielding the half-width 0.3 % for the conversion lines, except at the lowest energies, where there was considerable broadening due to the finite source thickness. The search for electron lines covered the whole region 25–1800 keV. The transitions found are listed with their energies in Table 1. Calibration was furnished by the 1064 keV line in Pb^{207}. The uncertainty in energy of the transitions 681, 764,

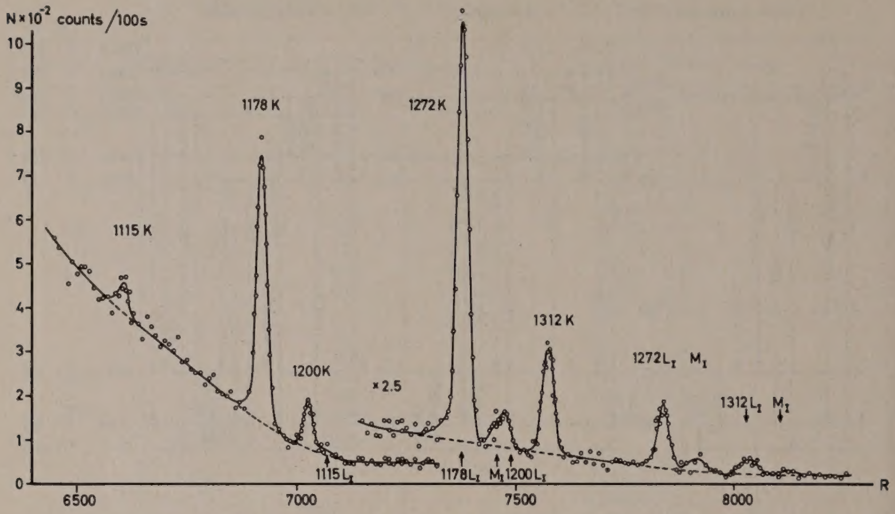

Fig. 3. Part of the gamma spectrum, recorded by means of the photo-electron method. The radiator was a 4 mg/cm² uranium foil.

and 1115 is mainly caused by counting statistics, whereas with the low energy lines the accuracy was impaired by electron straggling. The 94.3 keV *K*-line, being in the Auger region, could be identified because of its position in the space between the *KLL* and *KLM* groups. The 964 transition was found to be a close doublet (Fig. 2), as anticipated by Nathan [1]. Evidence was found for the existence of a 681 keV line.

Photo-electron measurements. Multipolarities

The photo-electron work was carried out with a source strength of about 100 mC. In order to absorb the β-radiation and still realize a compact source geometry the Tb_2O_3 powder was closely packed into a capsule of pure copper and irradiated, after which the Cu^{64} activity was allowed to decay. The photo-electron converters were U and Pb layers of thicknesses 0.6–4.4 mg/cm². The region 850–1700 keV was rather carefully scanned at a total line halfwidth of 0.4 %, resulting in the spectrum partly shown in Fig. 3. Some stronger lines were run at a resolution of 0.25 %. In particular the composite character of the 964 transition was again confirmed (Fig. 4) and the conversion coefficients of the components could be compared. The conversion coefficients of the pair were found to be the same within the limits of error (± 25 %), indicating the multipolarity E2 for the transitions 962.5 and 966.3.

In these measurements reference was made to a Co^{60} source for energy standards.

The 1076 keV transition reported by Nathan [1] as observed in coincidence with 197 γ was not seen here, from which it is concluded that its intensity is less than 1 %. The photo-spectrum reveals the presence of three new high energy transitions. The half-life of these lines was not carefully measured, but was seen to be 30 days or

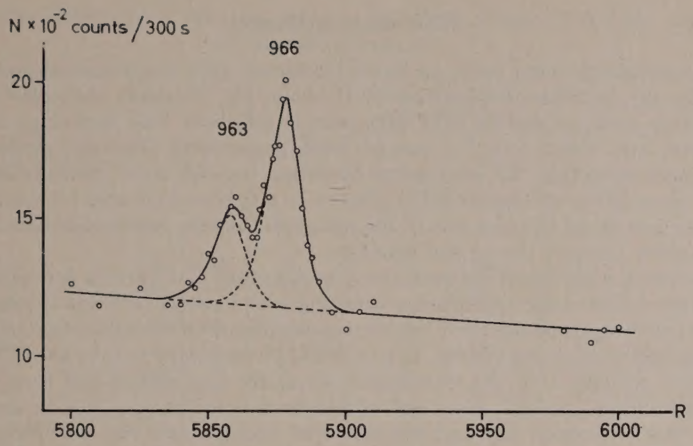

Fig. 4. The close doublet as appearing in the photo-spectrum. Resolution 0.2 %.

Table 2. Conversion coefficients in units of 10^{-4}.

Transition	Exp. value	Theoretical values		
		*E*1	*E*2	*M*1
1115	9.6	8.3	19	32
1200	7.2	7.3	17	27
1312	5.2	6.2	14	21

longer. The new transitions could not be due to impurities, however, since no long-lived rare earth isotope has been reported to emit prominent gamma rays of these energies. The additional transitions have all been observed in internal conversion as well as in the photo-electron spectrum and although the statistics were poor for the conversion lines a definite multipolarity could be assigned to them (Table 2). The relative conversion coefficients obtained from this work were normalized to an absolute scale by means of Nathan's value for the 1178 transition. The 1312 *K* conversion line nearly coincides with 1272 *L*, and the small contribution due to the *L* line was corrected for by using $K/L = 7.5$.

An upper limit of 0.3 % may be given for the intensity of possible transitions of energies higher than 1400 keV.

If all possible pairs of transition energies are added, the sums coincide with other line energies in such a way as to suggest a decay scheme identical to that of Nathan [1]. However, the additional lines reported here cannot be fitted into this frame without the postulation of new levels. Unfortunately energy considerations lead to alternative possibilities: lines 1115 and 1312.4 may deexcite a level at 1399.0 keV, or there may be a level at 1200 keV emitting the transitions 1199.9 and 1115.0 (Fig. 1). Whichever alternative is correct, one transition still remains to be located.

Electron coincidences

The experiments have been performed with an (*e*,*e*) coincidence spectrometer, essentially the instrument described by Gerholm [5], provided with plastic scintillators which were coupled to RCA 6810 photomultipliers. The resolving time of the coincidence unit was 2×10^{-8} s. Sources were prepared in the way outlined above. The channel accepting the conversion electrons was set to a transmission of 3 % yielding a resolution of 3 %, the other channel to 6 % resolution and 4 % transmission. The latter part faced the rear side of the source so that the continuous beta spectrum was observed through the mylar backing.

Coincidences were taken between the β-background and various conversion lines. It was found that some coincidence counting rate existed between the continuous spectra in each spectrometer half, which was attributed to a combination of Compton scattering and electron scattering. It was therefore necessary to take the difference in coincidence reading with the instrument set at the top and at the base of a line. Since this simple analysis does not eliminate a contribution due to coincidence between the conversion line and the scattered background, the coincidence effects obtained here may be expected to be accidentally too high. Further, the background impaired the statistics of the net effect.

The coincidence counting rate N_c observed between beta branch of counting rate N_β and a line (conversion probability $= \varkappa$) focused in the other channel (transmission $= \omega$) becomes $N_c = N_\beta \omega \varkappa \delta$, where δ is the fraction of a particular beta transition which goes through the γ-ray studied. The measurements aimed at determining the value of δ for as many beta and gamma rays as possible in order to check the decay scheme. As in general several beta branches contribute to N_β, the analysis had to begin with the highest branch. In computing N_c for the lower branches, the contributions of the higher branches to the coincidence effect were subtracted. The energy distributions $N_\beta(E)$ for the various beta rays were taken from the Fermi-plot published by Nathan [1]. Multipolarities were also taken from this paper. The values of δ so obtained contain an unknown factor, which was fixed by requiring $\delta = 1$ for β_3 and the lines 879.3 and 966.3. The results so obtained are shown in Table 3. Unfortunately no significant coincidences could be carried out with the highest energy conversion lines.

A coincidence effect has been observed here for the first time between β_4 and the 86.9 keV line. The fact that δ is larger than unity may partly be explained by an uncertainty in the beta intensity data.

The value of δ (β_4, 197) indicates a new beta branch to the 284 keV state. This evidence must, however, be considered very preliminary until the influence of scattering has been more carefully investigated. However, it is difficult to understand this effect in terms of coincidences between scattered radiation, since there should be no strong, high energy gamma rays feeding the 197 keV line.

Run 6, showing coincidences (β_3, 197), may be interpreted to prove either the existence of a beta transition to the 1049 level or alternatively a connecting gamma ray of 681 keV between the levels 966 and 284.

The combination (β_2, 216) shows a coincidence effect of the magnitude to be expected for the present decay scheme.

According to run 11 the 298 keV line is obviously not fed by β_3 or β_4. On the other hand it is in coincidence with β_2 (run 12) and the value of δ is in agreement with Nathan's decay scheme.

Table 3. The values of δ refer to the beta branch in column 6 and the conversion line in column 4.

Run number	E_β keV	Branch number	Conv. line	Coinc. per 1000^s	Coinc. per 1000^s reduced value		δ-values	
					Beta branch to level at keV	Coinc. per 1000^s	δ_{exp}	δ_{Nathan}
1	1360	4	L 86.8	44 ± 7	87	44 ± 7	2.5 ± 0.5	1
2	1000	4	L 86.8	47 ± 8	87	47 ± 8	1.6 ± 0.4	1
3	1360	4	K 197.0	5 ± 3	87	5 ± 3	0.9 ± 0.6	0
4	1285	4	K 197.0	8 ± 3	87	8 ± 3	1.2 ± 0.5	0
5	1000	4	K 197.0	16 ± 3	87	16 ± 3	1.8 ± 0.4	0
6	627	3; 4	K 197.0	25 ± 4	966	15 ± 7	$(3 \pm 1.5)10^{-2}$	0.9×10^{-2}
7	459	2; 3; 4	K 197.0	66 ± 6	1265	33 ± 14	0.1 ± 0.05	0.02
8	627	3; 4	K 215.6	7 ± 6	966	7 ± 6	$[6 \pm 5]10^{-2}$	0
9	589	3; 4	K 215.6	7 ± 7	966	7 ± 7	$(4 \pm 4)10^{-2}$	0
10	459	2; 3; 4	K 215.6	6 ± 4	1265	6 ± 4	$(8 \pm 5)10^{-2}$	9×10^{-2}
11	627	3; 4	K 298.6	-3 ± 4	966	-3 ± 4	$\leqslant 2.10^{-2}$	0
12	459	2; 3; 4	K 298.6	16 ± 4	1265	16 ± 4	0.49 ± 0.1	0.58
13	627	3; 4	K 879.3	6 ± 1	966	6 ± 1	0.50 ± 0.1	0.60
14	459	2; 3; 4	K 879.3	12 ± 2	1265	2 ± 3	0.3 ± 0.4	0.35
15	627	3; 4	K 962.5 K 966.3	5 ± 1	966	5 ± 1	0.49 ± 0.1	0.40
16	459	2; 3; 4	K 962.5 K 966.3	16 ± 2	1265	7 ± 3	1 ± 0.4	0.30

The high coincidence counting rate of run 16 seems to be in disagreement with the decay scheme. A very strong angular correlation effect might be partly responsible for this deviation, although the construction of the spectrometer is such that an average is taken over the region $\pm 60°$ of correlation angles.

Discussion

Most features of the decay scheme proposed by Nathan [1] are supported by the data presented here. Sum-up relations have proved to be correct with more accurate transition energies, and coincidences do show expected effects in most cases.

Nathan's assignment of $K = 2$ and $I = 2$ (γ vibration) to the level at 966 keV is supported by the intensity data found in this work. The branching ratios to the ground state rotational band as predicted by the collective model are 0.70:1.0:0.05, and the values experimentally found are 0.45:1.0:0.06.

Although evidence has been found for at least two additional levels of odd parity, their location in the decay scheme cannot at present be definitely decided, although the level at 1399 keV does give better energy fit than the alternative 1200 level. It is interesting to speculate on the possibility of an odd parity vibrational level ($K = 0$, $I = 1$). The level energy 1200 keV seems reasonable as compared to the only known analogous case in this region [6]: the 963 keV level in Sm^{152}. However, the theoretical branching ratio to the lowest levels is $B\,(1-, 0+)/B\,(1-, 2+) = 0.5$, whereas the experimental value is 1.2. A similar interpretation of the 1399 keV level as the next

Table 4. Possible spin of Tb^{160}.

The log ft values actually observed by Nathan are: $\simeq 12$ to the 87 keV level and $\simeq 8$ to the $K = 2$ states.

I, K	π	Remarks
>4	$\pm$	87 keV level would not be populated
4	+	Trans. to 87 keV would be 2nd forbidden and $K-$ forbidden, whereas trans. to 284 keV level would be allowed but $K-$ forbidden
4	−	Trans. to 1265 keV state would be 2nd forbidden
3	+	Allowed (GT) trans. to states at 966 keV and 1049 keV
3	−	Allowed (GT) trans. to states at 1265 keV and 1359 keV. Assignment compatible with branch to 284 keV level as reported here
2	+	Allowed trans. to states at 966 keV and 1049 keV
2	−	Allowed transition to 2− state at 1265 keV
1	+	2nd forbidden trans. to state at 1049 keV
1	−	2nd forbidden trans. to state at 1359 keV
0	$\pm$	Would not populate 3± states

member of the $K = 0$ band requires the branching ratio $B(3-, 2+)/B(3-, 4+) = 0.75$. The reduced intensity ratio found here actually is 0.75.

Nathan has identified in this nucleus the first two members of a quadrupole vibrational band, $K = 2$, and an odd parity band, $K = 2$ (see Fig. 1). The spacing, due to rotational energy, is evidently well calculable by means of the expression $(h^2/2\mathfrak{J})\,I(I+1)$, by use of the same moment of inertia as for the ground state band. If this were to hold even for the $K = 0$ odd parity band, the energy spacing between the 1− and 3− levels should be 145 keV. The second member would then rather coincide with the adjacent 3− level, proposed by Nathan to have $K = 2$. A reinterpretation of this level as having $K = 0$ would, however, be in conflict with the experimental branching ratio to the 2+ and 4+ rotational levels.

The spin of Tb^{160} has not yet been measured. The beta branching ratios and level assignments being rather well known, it would seem possible to make a theoretical spin assignment for Tb. The relevant arguments have been summarized in Table 4. This indirect experimental evidence may be compared to the predictions of the single particle model of spheroidal nuclear fields [7]. The 65th proton is in a state of $\Omega = \frac{3}{2}$, even parity. There is some doubt about the state of the 95th neutron, since the single particle levels 5/2+, 5/2−, and 3/2− lie rather close and their order need not necessarily be exactly as shown in the Nilsson diagram. The possible alternatives for the spin-parity of Tb^{160} are consequently 4+, 4−, 3−, 1+, 1− and 0. It is evident from Table 4 that 3− is the most probable assignment. This assignment implies that the corresponding neutron state is 3/2−. The addition of Ω_i evidently occurs according to the coupling rules of Moszkowski and Gallagher [8].

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Note added in proof.—A recent work on the levels of Dy^{160} has come to our attention (E. P. Gregoriev, B. S. Dzhelepov, A. V. Zolotavin, O. E. Kraft, B. Kratsik, and L. K. Peker, Izvestia Akad. Nauk. USSR *22* (1958) 101 [in Russian]). Transitions of 1112 keV and 1201 keV are reported as following the decay of Tb^{160}. A level scheme is presented, based on auxiliary data from the decay of Ho^{160}. Their decay scheme is identical to that of Nathan, except that an odd parity level at 1200 keV has been added.

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